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ACCURACY PERFORMANCE OF ELORAN FOR MARITIME APPLICATIONS

ABSTRACT

E-Loran, or enhanced Loran, is the latest in the longstanding and proven series of low frequency, LOng-RAnge Navigation systems. eLoran evolved from Loran-C in response to the 2001 Volpe Report on GPS vulnerability. It improves upon previous Loran systems with updated equipment, signals, and operating procedures. The improvements allow eLoran to provide better performance and additional services when compared to Loran-C, and enable eLoran to serve as a backup to satellite navigation in many important applications.

Different applications impose specific requirements on the navigation system's accuracy, availability, integrity and continuity performance. In the maritime sector, accuracy requirements are the most stringent. In order to comply with the requirements of the International Maritime Organisation (IMO) for harbour entrance approach, eLoran has to provide an accuracy of better than 10 m (95%).

Achieving this target is possible if the eLoran navigation receiver is equipped with an up-to-date database of signal propagation corrections and if real-time differential Loran corrections are applied. When these conditions are met, the achievable accuracy is largely determined by the transmitters' geometry, signal strengths and atmospheric noise levels, but also by the mutual interference among eLoran stations. This is also referred to as Cross-Rate Interference (CRI) and is inherent to the way all Loran systems operate.

In this paper we present results of the eLoran research that is being conducted at the Czech Technical University in Prague (CTU) and the University of Bath (UK) in cooperation with the General Lighthouse Authorities of the United Kingdom and Ireland. In our work we have focused on questions that arise when considering introducing new eLoran stations into an existing network. This particular paper investigates the achievable accuracy performance of eLoran for maritime applications. The sources of measurement error in eLoran are reviewed, and an eLoran accuracy performance model is presented. Special attention is paid to the problem of CRI and possible ways of its mitigation.

This paper is an abridged version of a more detailed unpublished paper which can be found at the following address: http://safar.me.uk/pub/js_cl_pw_navsup_2010.pdf.

Keywords:
enhanced Loran, accuracy, maritime applications.

INTRODUCTION

Over the past years, the US Global Positioning System (GPS) has become an integral part of modern society. Be it on land, at sea or in the air, GPS is an important and often the primary means of Positioning, Navigation and Timing (PNT). Although its qualities make it, in many aspects, superior to other PNT solutions, there are also some serious shortcomings and vulnerabilities common to all Global Navigation Satellite Systems (GNSS) — present, as well as future (e.g. Galileo). These are largely a consequence of the extremely low GNSS signal levels at the surface of the Earth[1] and have been documented many times before [2, 4].

The concerns about the vulnerability of GNSS has sparked a renewed interest in the Loran PNT system, or rather in its upgraded version now widely called *enhanced Loran* or simply *eLoran*. The nature of the eLoran system makes its potential failure modes highly independent of GPS. eLoran is a terrestrial system, which operates in the low-frequency band, uses high-power transmitters and completely different navigation signals. Its signals are also data modulated, which enables eLoran to deliver differential corrections, integrity messages and other data to users. Despite the fundamental dissimilarities, both eLoran and GPS are ranging systems and the observables from these systems can naturally be combined into an integrated position solution. In recent years, considerable effort has thus been put into investigating whether eLoran can provide a viable backup to GPS as well as other GNSS.

In Europe, the General Lighthouse Authorities of the United Kingdom and Ireland (GLAs) lead the way in eLoran research. The work presented in this paper is part of the GLAs' effort to develop a comprehensive eLoran coverage and performance model. Coverage prediction in general tells us over what geographical region the eLoran service can be used and to what level of quality. There are four system requirements that need to be assessed in order to satisfy the required navigation performance. These are accuracy, availability, continuity and integrity. This paper concentrates only on the accuracy performance of eLoran.

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[1] The received minimum RF signal level for block IIR-M/IIF GPS satellites, for example, is –158.5 dBW [17].

ACHIEVABLE POSITIONING ACCURACY OF ELORAN

When referring to accuracy of a positioning system, we need to distinguish between its absolute accuracy and repeatable accuracy. In [12], the *absolute accuracy* is defined as the accuracy of a position with respect to the geographic or geodetic coordinates of the Earth. The *repeatable accuracy*, then, is the accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigational system. Due to the nature of low-frequency signal propagation, Loran systems may suffer from large measurement biases, resulting in absolute accuracy on the order of hundreds of meters. However, Loran's repeatable accuracy is comparable to that of single-frequency (L1) GPS. In this paper, we explain how eLoran's absolute accuracy can be enhanced to the level of its repeatable accuracy, and we present a method for evaluation of eLoran's repeatable accuracy.

FACTORS AFFECTING ACCURACY

So what are the major factors that determine the accuracy of eLoran? eLoran is a ranging system, which means that the accuracy of our position fix is determined by the following three factors:

1. Accuracy of signal Time-of-Arrival (ToA) measurements.
2. Accuracy of the ToA to range conversion.
3. Geometry of the transmitter stations in view.

Transmitter geometry is a crucial factor in obtaining a good position fix; however, the impact of geometry on the accuracy performance of a ranging system is well understood [3] and will not be discussed in this paper.

Accuracy of the ToA to Range Conversion

One of the most important sources of error in Loran systems is due to spatial and temporal variations in the signal propagation velocity. The propagation velocity of Loran ground wave signals is a function of the Earth's surface conductivity and it also depends on the parameters of the atmosphere (temperature, pressure, humidity). Terrain elevation can also affect the signal propagation time, as eLoran ground waves obediently follow the Earth's surface and therefore travel a longer path than the theoretical point-to-point distance over an assumed smooth Earth. All of the factors mentioned above limit our ability to accurately convert the signal ToA measurements into distances, and thus contribute to the overall positioning error. In eLoran we account for these factors by means of so-called *Primary* (PF), *Secondary* (SF) and *Additional*

Secondary Factors (ASF). PF and SF allow us to model the signal propagation in the Earth's atmosphere over an all-sea water path. Any additional delay due to propagation over land is then taken into account using ASFs. In order to achieve the best possible positioning accuracy, ASFs in the area of interest need to be measured and stored in the receiver. Fluctuations in the ASF values should also be monitored and broadcast to the user in the form of differential corrections, e.g. using the eLoran data channel. Not taking ASFs into account can lead to ranging errors of up to 2 km [17]. Applying them correctly, on the other hand, gives the full eLoran accuracy, which approaches the repeatable accuracy of the system.

eLoran signal propagation may also be adversely affected by the presence of nearby conducting structures whose dimensions are an appreciable fraction of the signal carrier wavelength (e.g. bridges). Such structures can “absorb” some of the eLoran energy and re-radiate it [14]. The effects of re-radiation need further investigation and will not be discussed here.

Accuracy of the ToA Measurement

The third (and most varied) group of factors determining the positioning accuracy are those that affect our ability to accurately measure the actual ToAs of the eLoran signals. The ToA measurements are made in two stages. First, coarse measurements are made based on the shape of the leading edge of the eLoran pulse. When the approximate ToAs are known, the carrier phase of individual eLoran ground wave signals is measured to obtain more accurate ToA estimates. It is therefore the carrier phase distortion, which will be of interest in the following.

The ToA measurement errors are predominantly determined by the Signal-to--Noise Ratio (SNR) of the received signals. In the Loran frequency band, the dominant sources of noise are *atmospheric noise*, which is caused by lightning discharges, and *man-made noise* from, for example, switch-mode power supplies. Other sources of noise may include transmitter pulse timing jitter or receiver related noise. The latter is believed to be a minor component with modern eLoran receivers though [5].

Uncorrelated ToA measurement errors (e.g. due to atmospheric noise) can be suppressed by integrating (averaging) a certain number of received pulses before taking the measurement. This effectively increases the SNR of the received signals, but at the same time it places limitations on the allowable dynamics of the user platform.

Besides noise, another important source of ToA measurement error is interference caused by other radio signals. We can distinguish two types of interference to eLoran — *Carrier Wave Interference* (CWI) and *Cross-Rate Interference* (CRI). CWI originates from radio services operated near the eLoran frequency band and was considered a major threat for Loran-C. With today's receivers though, most of the out-band CWI can effectively be suppressed, therefore CWI is no longer expected to be an issue. CRI emanates from eLoran itself and is currently the major source of interference to eLoran. What exactly is the cause of CRI then?

eLoran transmitters are organised in groups of usually 3 to 5 stations called 'chains'. The stations periodically broadcast groups of 8 or 9 specially shaped low--frequency, high-power, pulses. The interval between successive repetitions of the groups of pulses is unique to each chain and known as the *Group Repetition Interval* (GRI). Careful selection of GRIs and transmission times ensures that stations operating in a chain do not interfere with each other. However, the nature of the system is such that the signals from different chains overlap from time to time and may introduce errors into our ToA measurements – this is referred to as CRI.

Another effect of CRI is *transmitter dual-rate blanking*. Some Loran transmitters are dual-rated, i.e. they broadcast signals on two GRIs, and such transmitters are periodically faced with the impossible requirement of radiating overlapping pulse groups simultaneously. During the time of overlap, those pulses of one group that overlap any part of the other group's blanking interval are suppressed. The *blanking interval* extends from 900 µsec before the first pulse to 1600 µsec after the last.

Maritime eLoran

Accuracy is the major factor affecting the suitability of eLoran for maritime navigation. IMO standards for the region of Port Approach specify a stringent accuracy requirement of 10 meters (95 percent of the time). A number of studies in the past have shown that accuracies better than 10 m are achievable [1, 9]. Table 1 summarises measures that need to be taken in order to meet the 10 m accuracy requirement in the maritime environment.

Table 1. Meeting the maritime accuracy requirement

Accuracy Limiting Factor	Mitigation
Poor geometry	Installation of additional eLoran transmitters, perhaps using low power mini-eLoran stations as coverage gap fillers
ASF spatial variation	Detailed ASF maps stored in receivers
ASF temporal variation	Differential reference stations
Uncorrelated noise	Integration time ~ 5 sec is acceptable
Man-made noise	Careful receiver antenna installation

From what has been said so far, it follows that the major error sources in maritime eLoran are the residues of atmospheric noise, transmitter related noise, and CRI. These factors are also at the heart of the GLAs' coverage and performance model and will be investigated in greater detail in the following section.

THE GLA COVERAGE AND PERFORMANCE MODEL

The GLAs' coverage and performance model is implemented in the MATLAB^{TM} environment. In the accuracy module of the coverage software, we first decide which eLoran stations to include in the analysis and we set up a region over which coverage is required. The coverage region is divided into grids consisting of rectangular elements of equal sizes, typically 0.1° in latitude by 0.1° in longitude. At each point in the grid the individual coverage limiting factors are modelled and the resulting data arrays are stored. When required, for coverage computation, these are then loaded into memory.

The level of repeatable accuracy is highly dependent on the variance of the measured ToA values. The higher the variance of the ToA, then the poorer is the positioning accuracy. The main driver of ToA variance is the signal-to-noise ratio (SNR) of the received signal. The lower the SNR, the higher the ToA variance and therefore the poorer the positioning accuracy. The calculation of SNR requires knowledge of the signal strength (or field strength) of the Loran signal, and the level of noise at the same location.

In the current implementation of the GLAs' coverage prediction software, ground wave field strength arrays are calculated using Millington's method. This employs a set of the 100 kHz propagation curves for different ground conductivities. Ground conductivity data is provided by a digital ground conductivity database developed at the University of Wales, Bangor, based on the World Atlas of Ground Conductivities [8].

As mentioned above, the dominant noise source in the Loran band is atmospheric noise. Atmospheric noise is computed at different percentiles and generated based on the model presented in ITU Recommendation P372-9 [7].

Most recently noise due to CRI has also been taken into account, as will be described below.

In addition to ground wave, the effect of sky wave propagation also needs to be taken into account, since there are likely to be geographical locations where the *wanted* ground wave is interfered with by its *unwanted* copy arriving via reflection from the ionosphere. Sky wave field strength and sky wave delay arrays are computed. These are based on ITU recommendation 1147-2 [6].

Models implemented at Stanford University in their Loran Coverage Availability Simulation Tool [10] were also studied and we are in the process of incorporating these into our software.

When all the data arrays are available, algorithms within the software then test each grid point to see whether the eLoran signals meet certain acceptance criteria. For example, a signal of a particular station is used in the accuracy analysis only if its SNR is higher than –10 dB and the sky wave field strength to ground wave field strength ratio and sky wave delay are within the limits prescribed by the receiver Minimum Performance Standard [11]. With the (possibly) reduced set of signals at each grid point, repeatable accuracy is calculated and accuracy plots are generated. Selected parts of the model will now be presented in greater detail.

Modelling Errors Due to Atmospheric Noise

As explained earlier, atmospheric noise is one of the major sources of measurement error in eLoran. Our software allows us to evaluate the signal-to-atmospheric noise ratio for each station used in any point of the coverage area. Further, in [10] Lo *et al.* presented the following equation for the conversion of SNR to pseudorange measurement variance:

$$\sigma_s^2 = c_1 + \frac{337.5^2}{N \cdot SNR}, \tag{1}$$

where:
c_1 [m^2] accounts for transmitter related noise, which is assumed to be 6 m, one sigma ($c_1 = 36$ m^2) [10], N is the number of pulses used in signal integration, and SNR is the SNR of a single pulse, expressed as a linear ratio.

No explanation is given in that paper as to how this equation had been obtained. However, we have verified the equation ourselves both analytically and by numeric simulations; and we can confirm that the second term on the right hand side of Equation 1 gives an accurate estimate of pseudorange measurement variance under the assumption of white noise, at least in the range of SNR from –10 dB to +40 dB. This part of the equation is therefore being used in our coverage prediction software to model the measurement errors introduced by atmospheric noise. The usage of the c_1 constant is discussed further in this paper.

Modelling Errors Due to CRI

In order to meet the stringent eLoran standards, the impact of CRI within the system must be greatly reduced. This can, for example, be achieved through *CRI blanking* at the receiver end. With this technique, the eLoran receiver detects the pulses likely corrupted by CRI and discards them. The more pulses that are blanked, however, the higher is the influence of atmospheric noise and other disturbances on the ToA measurements, as the signal power available for tracking decreases significantly. We have designed methods of evaluating this blanking loss [16] and recently extended these to include the impact of sky wave borne CRI [15] (the presence of sky waves increases the probability of collision between the interfering pulse trains, depending on the sky wave delay). An example plot showing the blanking loss for one of the European stations is included in the case study below (figure 1).

Accounting for Other Sources of Error

Earlier in this paper we presented Lo *et al's* formula for the estimation of pseudorange variance due to atmospheric noise and *transmitter timing jitter* (Equation 1). In this formula the impact of the transmitter noise was modelled by an additive constant, equal to the equivalent in range of the assumed variance of the pulse timing jitter. We argue that this approach is too pessimistic, and we suggest a slightly modified version of this equation as explained in [15]:

$$\sigma_s^2 = \frac{337.5^2}{N \cdot SNR} + \frac{c_1}{N} + c_2 , \tag{2}$$

where:
N, SNR, and c_1 are as described in Equation 1 and c_2 [m^2] accounts for *other sources of variation* in the pseudorange measurements.

These may include: background CRI-induced noise caused by signals from distant interfering stations that cannot be processed out, residual CWI, receiver related noise, etc. The value of the c_2 constant has to be found experimentally. We have found that $c_2 = 12$ m^2 gives a good agreement with measurements from the GLAs' differential eLoran reference station in Harwich.

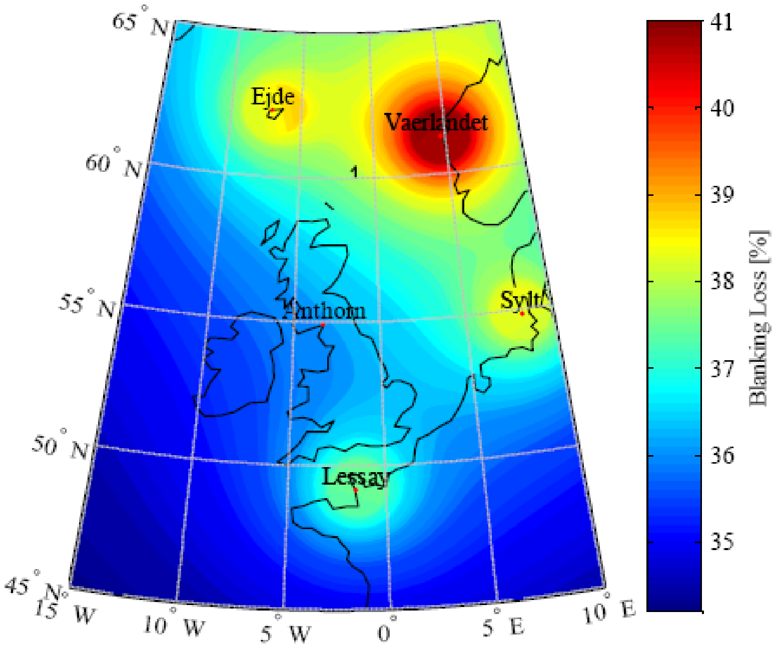

Fig. 1. Percentage of pulses blanked for the Anthorn station; height of the ionosphere: 91 km

Estimating Positioning Accuracy

In [16] we explained how the errors in pseudoranges translate into the position domain, assuming that the receiver utilises the Weighted Least Squares (WLS) position determination algorithm. We showed that the repeatable 2DRMS (Twice the Distance Root-Mean-Square) position accuracy can be estimated as:

$$\delta_{2DRMS} = 2\sqrt{\mathbf{C}_{1,1} + \mathbf{C}_{2,2}}\,, \tag{3}$$

where:

$\mathbf{C} = \left(\mathbf{A}^{T}\mathbf{R}^{-1}\mathbf{A}\right)^{-1}$, $\mathbf{A}$ is the direction cosine matrix, which describes the geometry of eLoran stations relative to the user's position, and $\mathbf{R}$ is the pseudorange measurement covariance matrix.

This matrix is composed of the variances on each measurement obtained as described earlier.

Based on the value of δ_{2DRMS}, our software also estimates the R95 (95 percent radius) error. This estimation however is only valid under the assumption of Gaussian-distributed measurement errors.

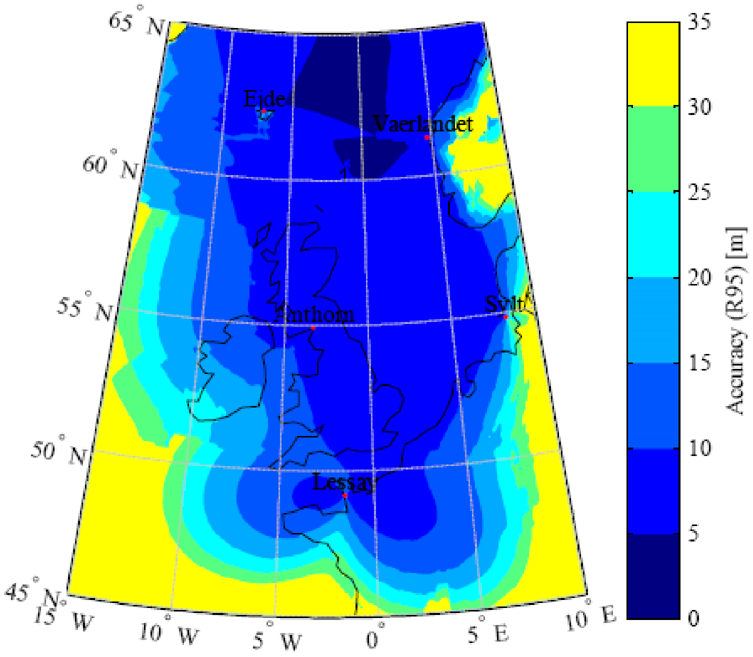

Fig. 2. Contours of repeatable eLoran accuracy (95%)

CASE STUDY

We will now demonstrate the use of the tools presented in this paper through a case study investigating the achievable repeatable accuracy of eLoran over the British Isles. Our transmission network will be formed by the 14 transmissions from the 9 European transmitters currently in operation, configured according to Appendix A. We assume that CRI within the network is mitigated through blanking. CRI originating from other Loran transmitters than those in Appendix A will not be considered in this study. The signal integration time is assumed to be 5 seconds.

The assessment of repeatable accuracy over the specified region followed the steps described in the previous section. First, the ground wave field strength arrays were calculated. We assumed that signal phase measurements are made 4 dB below the peak of the pulse, which corresponds to the location of the standard zero crossing on an undistorted eLoran pulse. Using the ITU noise model and the ground wave field strength arrays, SNR for all stations assumed in our analysis were estimated. In accordance with common practice [10], we used annual atmospheric noise not exceeded 95% of the time.

For each station, range limits were calculated based on the sky wave propagation parameters. Sky wave field strength values at 99 percentile for the winter night time period were used, providing a conservative estimate of own sky wave interference. The height of the ionosphere was assumed to be 91 km. The effects of sky wave propagation were also taken into account when evaluating the blanking loss for each station incurred as a result of mitigating CRI. Figure 1 shows the predicted blanking loss values for one of the transmitter stations used in our analysis.

Finally, pseudorange measurement variances were estimated using Equation 10 and the 2DRMS positioning accuracy was calculated using Equation 11. Figure 2 then shows the predicted R95 accuracy plot.

CONCLUSIONS AND FUTURE WORK

In this paper we have presented a set of tools for the assessment of eLoran accuracy performance, developed by a joint effort of the General Lighthouse Authorities of the United Kingdom and Ireland, the Czech Technical University in Prague, and the University of Bath. We have generated repeatable accuracy plots for the GLAs' service area using the current configuration of the European Loran transmitters. In doing so, we assumed that perfect ASFs were provided to the user, so that any biases in the measurements were eliminated. The resulting plots suggest that sub-10 m repeatable positioning accuracy should be achievable over most of Britain's coastal waters. Areas of insufficient coverage can be found on the west coast of Britain and over Ireland.

In the future we intend to include differential eLoran in the model. This requires a study of spatial decorrelation of the differential corrections as the user receiver moves away from the reference station. Also the accuracy of ASF maps used in user receivers needs to be assessed and included into the overall error budget. We also want to concentrate on collecting data to help model the effects of CRI. This should include modelling of advanced CRI mitigation methods, such as CRI cancelling, and background CRI noise from distant stations that cannot be processed out. Work is also underway on the availability and continuity components of the coverage prediction software. These will be described in follow-up papers.

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APPENDIX A

Table A1. European Loran stations

GRI ID and Station Name	Dual-Rate Blanking
6731 Lessay	Priority 6731
6731 Soustons	Not dual-rated
6731 Anthorn	Not dual-rated
6731 Sylt	Priority 7499
7001 Bø	Priority 9007
7001 Jan Mayen	Priority 9007
7001 Berlevag	Not dual-rated
7499 Sylt	Priority 7499
7499 Lessay	Priority 6731
7499 Værlandet	Priority 7499
9007 Ejde	Not dual-rated
9007 Jan Mayen	Priority 9007
9007 Bø	Priority 9007
9007 Værlandet	Priority 7499

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